

## Evaluation of charging infrastructure requirements and operating costs for plug-in electric vehicles

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### HIGHLIGHTS

- PHEVs: all charging infrastructure options show operating cost reduction
- PHEVs: meager operating cost reduction with more non-home charging locations
- Unlike PHEVs, sufficient non-home EVSE must be installed to satisfy BEVs
- BEV60: 88% of drivers need only LEV2 home charging; EVSE everywhere satisfies 96%
- BEVs: optimal distribution is 80%, 9% and 11% EVSE at home, work and other places

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### ABSTRACT

Plug-in electric vehicles (PEVs), including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), have the potential to improve the energy and environmental landscape of personal transportation, but face a hurdle of access to charging infrastructure. Additionally, the types, locations, and quantities of electric vehicle supply equipment (EVSE) that will be required are not well established. This study investigates the charging infrastructure requirements from the perspective of PEV operating cost and BEV feasibility. California was selected as the research region and PEV parameters were selected based on the early deployed vehicles available in the emerging commercial market. To minimize operating cost, an optimal charging strategy based on 24 h travel patterns is proposed. Results indicate that charging time strategy is the most important factor in reducing PEV operating cost while greater numbers of charging locations provide diminishing benefits for PHEVs. Higher charging power capability, combined with an acceptable charging time strategy offer only slight benefits for PHEVs, but charging power is an important factor in increasing BEV functionality and decreasing public charging requirements. The approximation of the electric vehicle supply equipment (EVSE) needed at different types of locations (e.g., home, work place, shopping) is proposed based on an optimal charging strategy.

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## 1. Introduction

Plug-in hybrid electric vehicles (PHEVs) having onboard electricity and gasoline storage, and battery electric vehicles (BEVs) powered solely by electricity, collectively referred to as plug-in electric vehicles (PEVs) herein, offer substantial environmental and energy improvements over petroleum powered vehicles [1]. The benefits provided by PEVs include reduction in fuel consumption, improvement in well-to-wheel efficiency, and decrease in greenhouse gas and pollutant emissions [2,3]. Due to these attributes, many federal, state, and local governments have advocated for PEV deployment, such as the Clean Car Rule and

Governor's Executive Order in California [4,5]; concurrently, major automakers are either manufacturing, or planning, PEV models.

Charging infrastructure will play a pivotal role on PEV deployment, and, in the absence of a proactive plan and schedule, is a major impediment to mass market adoption. Infrastructure limitations are particularly pertinent to BEVs due to their sole dependency on electricity, range limits, and long recharging time. However, little research has emphasized the differences in charging infrastructure requirements between PHEVs and BEVs. The charging infrastructure includes all of the hardware and software that ensures energy is transferred from the electric grid to the vehicle. It can be specified by location, power level, and charging time strategy.

Several studies evaluated the energy, emissions, and economic impacts of PEV adoption [6–13], while other studies [14–19]

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focused on detailed vehicle and grid operation to determine smart and optimal charging time strategies. Specifically, a group of studies [6,7,10,11,13] used either nationwide or statewide household travel surveys to investigate PHEV energy consumption, but the infrastructure scenarios were not fully illustrated and the charging time strategies were unsophisticated. Other research [8,9] utilized detailed electricity dispatch models and focused on the overall emission impacts of plug-in vehicles, but advanced charging time strategies were neither implemented nor explicitly explained. Two studies [12,16] include detailed PHEV dynamic models to assess and optimize energy, economic, and environmental impacts, but include neither representative travel behavior nor detailed electricity cost considerations. A few studies [14,15,18] implemented optimal charging strategies and verified performance by minimizing the impact or the cost on the grid. However, these strategies were based on single daily charging events (overnight dwelling) due to the lack of realistic driving pattern data. Two final studies [17,19] conducted optimal charging strategies over a 24 h period to minimize vehicle operating costs with the real time price of electricity, and included real travel pattern data. Neither, however, considered ranges of charging power and charging location options.

As a next step, this paper attempts to systematically and comprehensively address (1) the relationship between charging infrastructure characteristics, PEV operating cost, and BEV feasibility, and (2) the infrastructure characteristics required to support PHEVs or BEVs, especially with regard to EVSE allocation. The goal is to evaluate the impact of realistic charging infrastructure options on real travel behavior in order to delineate PEV operating cost, BEV feasibility, and optimal charging strategy designed to identify the quantity and location of chargers and charger types in a given area. California was used as the focus of this study due to progressive PEV legislation and a relatively avid PEV marketplace (57% of U.S. PEVs were sold in California in 2011 [20]).

### 1.1. NHTS

The vehicle travel behavior data used in this paper are derived from the 2009 National Household Travel Survey (NHTS) [21]. Several processing steps were required in order to prepare the data for input to the model. In particular, data for California were selected, trips occurring without a personally owned vehicle were deleted, person-chain data were converted to vehicle-chain data, daily trips data with unlinked destinations or significant overspeed were deleted, and tours were organized into home based daily tours (first trip from home, last trip to home). 20,295 vehicles were selected covering 83,005 single trips with an average of 7.85 miles per trip and 32.13 miles per vehicle per day.

### 1.2. PEV charging rates

All the major investor owned utilities in California have released their specified PEV charging rates, including Pacific Gas & Electric (PG&E) [22], Southern California Edison (SCE) [23] and San Diego Gas & Electric [24]. In these service territories, customers can either combine their PEV charging with other consumption in the household, or independently with the installation of a separate meter. The latter option provides a time-of-use (TOU) rate which varies by season of the year, hour of the day, and by weekday and weekend. Fig. 1 is the E-9B rate schedule for PEV charging published by PG&E in the summer of 2011 [25], where the temporal trends reflect the general behavior of the system wide electricity demand. Similar TOU rates have been developed by the other utilities, but the PG&E rate shown is used in this work because it has three levels: peak, partial peak, and non-peak hour.

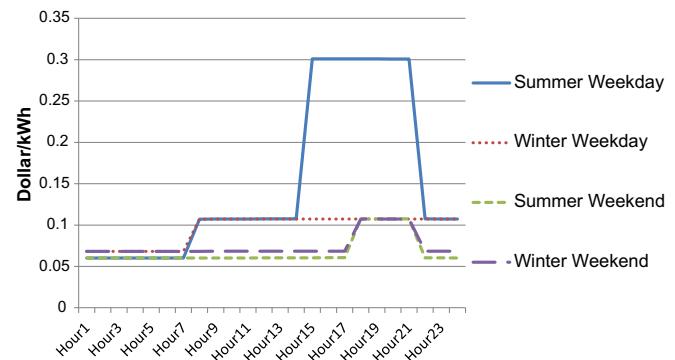


Fig. 1. PG&E residential PEV charging rates.

### 1.3. Vehicle information

Similar to other research [6,7,10,11,13], this study focuses on the macro scale of vehicle behavior where the detailed physical vehicle model was not considered; instead a parameterized vehicle operating and charging model was used. Table 1 shows vehicle parameters used in this study which were all derived from current production vehicles [26,27]. Gasoline price is assumed to be U.S. \$4.00 per gallon throughout this work.

## 2. Model

### 2.1. Non-optimal charging

The non-optimal PHEV charging model is based on previous work [6], with the addition of two scenarios: 1) smart charging, and 2) smart charging with fuel price. "Non-smart" charging strategies of immediate charging, delayed charging, and average charging are carried over from the previous study for comparison. For the smart charging and smart charging with fuel price strategies, a cost signal, e.g. Fig. 1, is incorporated into the model such that the driver is able to minimize charging cost during a specific dwelling activity, such as an overnight stay at home. The smart charging with fuel price strategy is designed specifically for PHEVs and compares operating costs for gasoline and electricity such that charging is not undertaken if electricity is more expensive than gasoline during that dwelling period. Charging power scenarios are chosen based on current charger specifications, standards, regulations, and future projections [28,29]. All charging infrastructure options are listed in Table 2.

### 2.2. Optimal charging

The optimal charging strategy considers an entire day's travel pattern and determines the optimal charging behavior based on a specific charging rate schedule. This differs from the above "non-optimal" methodology because it assumes complete knowledge of an entire day's travel and electricity price. This is not unreasonable in most cases as daily commutes are generally repetitive and electricity rates are currently published in advance.

Table 1  
Simulation parameters for all vehicles.

Vehicle type	MPG	Gasoline price (\$/gallon)	kW h/mi (DC)	All-electric range (miles)	Efficiency from grid to battery
HEVs	40	4.00	N/A	N/A	N/A
PHEVs	40	4.00	0.34	4–40	0.85
BEVs	N/A	N/A	0.31	45–100	0.85

**Table 2**  
Charging infrastructure options.

Vehicle types	Charging power (kW)	Charging location	Charging strategy
PHEVs	1.44, 3.3, 6.0	Home, home & work, anywhere	Immediate, delayed, average, smart, smart with fuel price, optimal
BEVs	1.44, 3.3, 6.0	Home, home & work anywhere	Optimal

The fundamental hypothesis is that drivers will adjust their charging behavior such that some objective can be achieved. In this case, the objective is the operating cost of PEVs, which mainly includes the electricity cost for BEVs and additional gasoline cost for PHEVs. This concept can prescribe the infrastructure required for PEVs which is particularly important for BEVs that require a non-home charging infrastructure. The methodology assumes that electric vehicle supply equipment (EVSE) is already available in prescribed locations. The optimal charging algorithm then outputs the locations that will be used during daily trips while minimizing charging costs. These locations then constitute the locations where EVSE should actually be installed. Although optimal charging has been implemented in previous studies [14–19], it has not been utilized to determine the locations for PEV infrastructure deployment. The method also serves as a baseline for the operating costs of non-optimal charging strategies.

Fig. 2 shows a schematic diagram of the model. Optimization requires knowledge of the whole day's vehicle travel pattern and the charging cost during each dwelling activity, which can be provided by the NHTS data and PG&E E-9B rate schedule, respectively. Given particular charging power limits, EVSE locations, battery capacity constraints, and energy conservation, the cost function can be minimized. The model outputs the location and duration of daily charging activity for each individual vehicle captured in the NHTS data. With the large and representative data set of NHTS, the summation of individual results is used to provide fleetwide characteristics.

Fig. 3 shows an example of BEV battery charging and discharging energy throughout the course of one day. Solid red circles represent trip starting points while checkered black circles signify ending locations. For example, a vehicle may make  $m$  trips during the course of 24 h (3 trips in the figure). The periods of battery state-of-charge (SOC) decrease (i.e., electricity consumption) are shown as  $y_1, y_2, \dots, y_m$ . Following each trip, a dwelling activity takes up a set of dwelling hours, indicated by  $x_{m1}, x_{m2}, \dots, x_{m\text{seg}(m)}$ . The optimization problem solves for the accumulated stored battery energy in each hour during each dwelling activity, represented by  $x_{ij}$ , required to fulfill a day's driving at the lowest cost. The formation of the optimization is given below (For

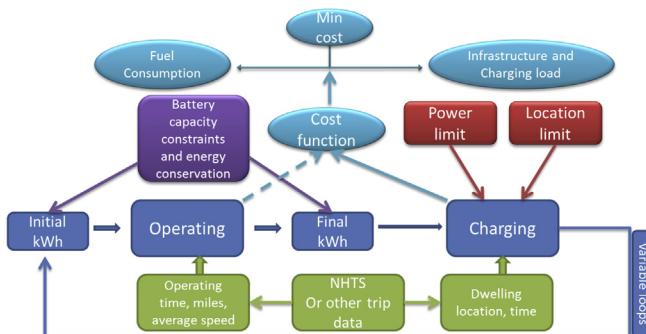


Fig. 2. PEV optimal operating and charging model.

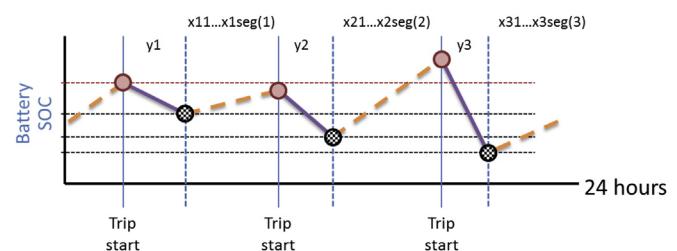


Fig. 3. Example of BEV optimal charging model.

interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

### 2.2.1. Variables

The SOC increase (or electricity recharged) during the  $j$ th hour in the  $i$ th dwelling activity is given by  $x_{ij}$ .

### 2.2.2. Cost function

The summation of the total charging cost is given by:

$$\sum_{i=1}^m \sum_{j=1}^{\text{seg}(i)} f_{ij} \times x_{ij} \quad (1)$$

where,  $f_{ij}$  is the charging cost per kW h (DC) during the  $j$ th hour in the  $i$ th dwelling activity.

### 2.2.3. Constraints

1. The charged and discharged energy are assumed to be equal for 24 h. So the energy conservation equality constraint is given by:

$$\sum_{i=1}^m \sum_{j=1}^{\text{seg}(i)} x_{ij} + \sum_{i=1}^m y_i = 0 \quad (2)$$

2. Inequality constraint: battery size. The window between the highest and lowest SOC points is not allowed to violate the battery size. In other words, as shown in Fig. 3, between any red circle (local maxima) and any black circle (local minima), the window has to be less than the battery capacity, ( $kwh$ ). From each red circle, there are  $m$  inequality constraints, as shown in the equations below. Consequently, there are  $m^2$  total constraints.

$$y_1 > -kwh \quad (3)$$

$$y_1 + \sum_{j=1}^{\text{seg}(1)} x_{1j} + y_2 > -kwh \quad (4)$$

$$y_1 + \sum_{j=1}^{\text{seg}(1)} x_{1j} + y_2 + \sum_{j=1}^{\text{seg}(2)} x_{2j} + y_3 > -kwh \quad (5)$$

$$y_1 + \sum_{j=1}^{\text{seg}(1)} x_{1j} + y_2 + \dots + \sum_{j=1}^{\text{seg}(1)} x_{(m-1)j} + y_m > -kwh \quad (6)$$

### 2.2.4. Bounds on the variables

The lower bound of  $x_{ij}$  is zero and the upper bound is a function of the following parameters (As shown in Eq. (7)):

1. The charging power level at the specific location which is derived from the charging location and power limits.
2. The time span of available charging, fixed by the NTHS data. For instance, if the first hour in the first dwelling activity starts at 30 min past the hour, then the  $x_{11}$  equals 0.5.
3. The AC to DC efficiency which is assumed to be a constant value in this study.

$$0 \leq x_{ij} \leq \text{power}_{ij} \times \Delta t_{ij} \times \text{charging efficiency} \quad (7)$$

### 2.2.5. Applied to PHEVs

The same concept can be applied to PHEVs with the objective to minimize total electricity and gasoline cost. As shown in Fig. 4, the light blue hashed circles indicate the final SOC if there were no engine assist (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

As before,  $y_1, y_2, \dots, y_m$  are known from the survey data. The values of  $x_1, x_2, \dots, x_m$  represent the actual SOC decrease when considering engine assist. So the equivalent battery work,  $e_1, \dots, e_m$  with positive values are added to account for the SOC difference:

$$y_i + e_i = x_i \quad (8)$$

A cost function is developed to minimize total operating cost:

$$\sum_{i=1}^m \sum_{j=1}^{\text{seg}(i)} f_{ij} \times x_{ij} + \sum_{i=1}^m \text{Dollar per Gallon} \times g_i \quad (9)$$

where, the extra term  $g_i$  is the gasoline consumption in the  $i$ th trip. With the equation below, the equivalent energy consumption  $e_i$  from the battery can be derived with the efficiencies of hybrid drive and BEV drive.

$$g_i \times \text{MPG} = e_i \times \frac{1}{\text{kW h per Mile}} \quad (10)$$

So Eq. (9) becomes:

$$\sum_{i=1}^m \sum_{j=1}^{\text{seg}(i)} f_{ij} \times x_{ij} + \sum_{i=1}^m f_i \times e_i = \sum_{i=1}^m \sum_{j=1}^{\text{seg}(i)} f_{ij} \times x_{ij} + \sum_{i=1}^m f_i \times (x_i - y_i) \quad (11)$$

where,

$$f_i = \text{Dollar per Gallon} \times \frac{1}{\text{MPG}} \times \frac{1}{\text{kW h per Mile}} \quad (12)$$

The equality and inequality constraints are the same as for BEV optimal charging. The optimization can solve  $x_{ij}$ , when and where to recharge the battery, as well as the amount of energy,  $x_i, g_i$ , provided by the battery and engine during vehicle operation. A Matlab linear solver (linprog) was used to solve the optimization problem.

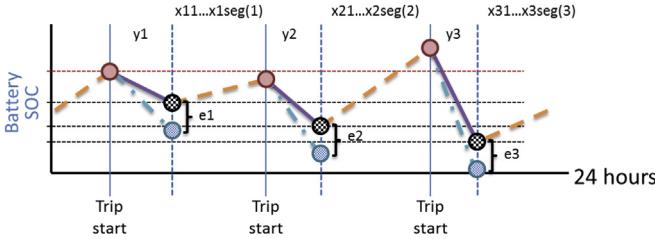


Fig. 4. Example of PHEV operating and charging model.

## 3. Results

### 3.1. PHEVs

#### 3.1.1. Operating cost

Fig. 5 shows the operating cost for PHEVs having 35 mile all-electric range with different charging infrastructure options. A HEV with a 40 MPG fuel economy is used as a comparative baseline. All the PHEV scenarios show significant operating cost reductions compared to the baseline. The results can be divided into six clusters based on charging time options; different charging locations show variation within each of the six clusters. As shown, charging time strategies reduce operating cost more significantly than charging availability (location). However, within each charging time strategy cluster, more charger locations reduce cost because driving on electricity is usually less expensive than driving on gasoline. More charging locations implies more gasoline reduction [6], and hence lower cost.

From a PHEV cost perspective, a higher charging power is not necessarily good. Firstly, a EVSE upgrade is required, which, though not considered in this paper, is a significant overall cost penalty. Secondly, if a PHEV is charged inappropriately, for example immediate or delayed charging as shown in Fig. 6, high power leads to higher operating cost, even if slightly more gasoline reduction can be achieved [6]. Thirdly, a benefit of higher power charging occurs only during smart and optimal charging when non-home charging locations are used. However, this further reduction in cost from 1.44 kW Level 1 to 6 kW Level 2 charging is limited to just 50 cents/100 miles.

#### 3.1.2. Charging profile

The charging profile from “non-smart” charging strategies was fully demonstrated in previous work and is shown in Fig. 6 [6]. The U.S. Department of Energy EV project provides real world data that verify these previous model results. Compared to the immediate charging shown in Fig. 6, the real charging profile in Nashville [30] shows the same diurnal trend with a peak in the early evening. The immediate charging strategy is essentially optimal for that region since no time-of-use pricing has been established there. Charging as soon as possible is consequently more convenient while posing no financial impact.

Fig. 7 shows the annual average charging power over the course of 24 h with no restrictions on charging locations (i.e., EVSE located at all dwelling locations) for an advanced charging time strategy. In Fig. 7, the charging profile at home for smart charging with fuel price shows the same trend as the real charging profile recorded in San Diego [30] during the course of 24 h with a peak at midnight. The main reason is that both PG&E's rates used in the model, and SDG&E's rates in the San Diego area EV project, have minimum electricity prices starting from midnight.

These results demonstrate that the model predicts well the charging profile trend when the key conditions are the same; e.g., charging location and electricity rates. Similarly, the hypothesis is verified that drivers' charging behavior follow the objectives of reducing cost and being convenient.

#### 3.1.3. Case analysis

By using the model, results from numerous scenarios can be generated in terms of fuel consumption, charging profile, operating cost, and EVSE allocations. Two cases are shown below focusing on EVSE allocation.

**3.1.3.1. Lowest cost, least gasoline consumption.** With a goal to minimize charging cost while also reducing gasoline consumption, and the assumption that charging is available at all locations, the smart charging with fuel price strategy demonstrates a general

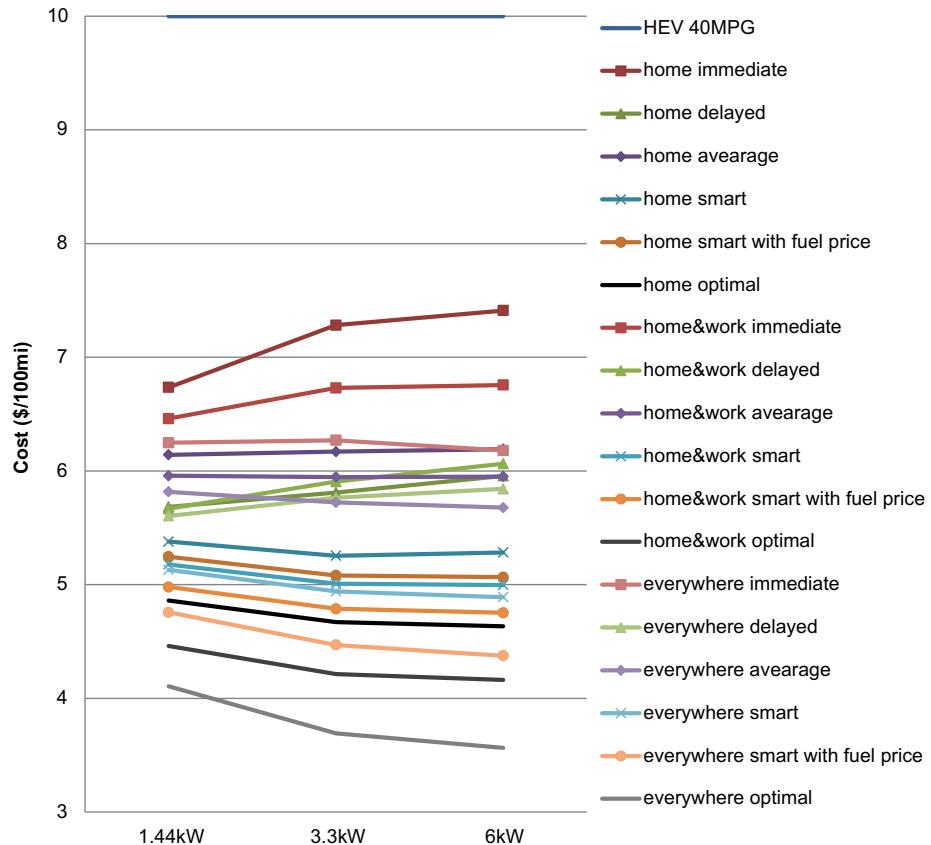


Fig. 5. PHEV35 operating cost.

view of the charging profile at different locations. For the scenario shown in Fig. 7, charging activities at non-home locations account for 56% of the total charging events, while the additional gasoline and cost reduction compared to home-only charging is relatively small. Compared with HEVs, around 70% gasoline reduction can already be accomplished by PHEV35s with home charging only [6]. As a result, it appears that relatively little additional energy or environmental benefit can be obtained from PHEVs, regardless of the breadth and expense directed towards non-home charging locations.

**3.1.3.2. Lowest cost, regardless of gasoline consumption.** A similar scenario can be examined whereby operating cost is minimized, but in this case, there is no particular goal to reduce gasoline

consumption. It should be noted that a slight slope was added into the original cost function from the electricity rate structure according the basic electric demand in California, in order for the optimization algorithm to find a solution for this scenario. Fig. 8 shows that for optimal cost reduction, most energy will be drawn from home charging (79%). However, the charging activity distribution (number of charging events) is 67%, 12% and 21% for home, work and other locations, respectively. This serves as an indicator for EVSE allocation. In other words, many EVSE installations would be needed at non-home locations to provide the lowest cost operation, even though most are rarely used. Table 3 details the distribution of charging activity and energy distribution by location.

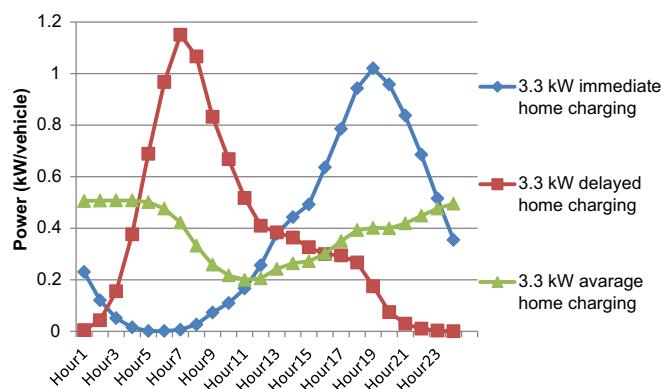


Fig. 6. PHEV35 diurnal charging profile for home immediate, delayed and average charging.

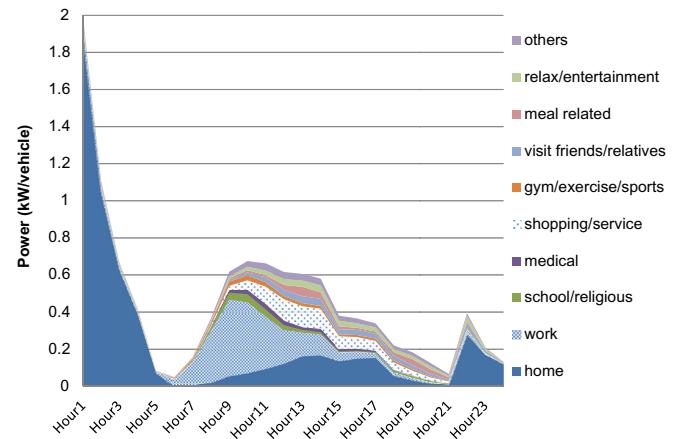


Fig. 7. PHEV35 annual charging power distribution for smart charging with fuel price.

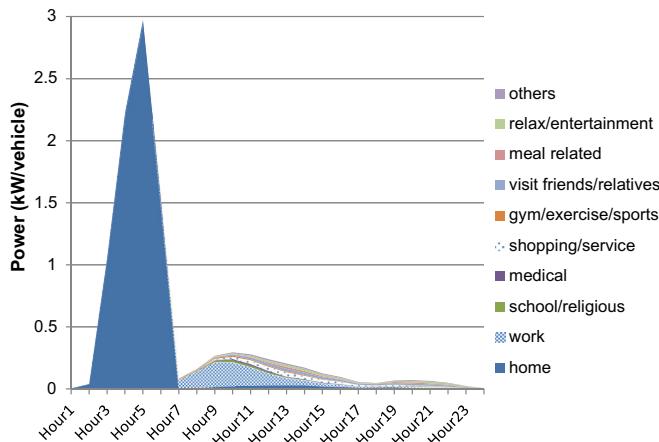


Fig. 8. PHEV35 annual charging power distribution for optimal operating and charging.

As shown in Table 3, shopping and meal related activities represent the most used public charging locations; however, the average charged energy is only around 2 kW h, amounting to only about 5 miles of additional range per vehicle per day. As mentioned in the previous section, more charging locations lead to more operating cost reductions, but infrastructure cost and EVSE capacity factors (not considered herein) should be taken into account when assessing the deployment of non-home EVSE. More economic analysis needs to be conducted to fully understand the feasibility of installing public charging infrastructure for PHEVs to accomplish a relatively small amount of operating cost reduction.

### 3.2. BEVs

#### 3.2.1. Feasibility

Limited range is the most important operational barrier faced by BEVs. As a result, an index is introduced as a measure of the range limit in terms of driving behavior. Feasibility is defined as the ratio of the number of vehicles that could meet normal daily operating behavior as BEVs to the total number of vehicles. A high feasibility ratio would therefore be required for mass BEV adoption. BEV range and availability of charging infrastructure influence feasibility, as shown in Fig. 9. It should be noted that behavior changes can also affect BEV feasibility, as assumed in other studies [31]. The methodology herein assumes that drivers make no changes to their normal vehicle usage habits. This represents a “worst case” scenario for BEVs and EVSE infrastructure. As a result, the high feasibility shown here is a testament to the potential of current BEV technology to dramatically shift our petroleum transportation paradigm, if appropriate market forces occur.

Table 3

Distribution of charging activities and energy for PHEV35 optimal charging.

Locations	Dwelling count (%)	Charging count (%)	kW h/Charging event	Total energy delivered (%)
Home	36	67	7.26	79
Work	13	12	5.26	11
School/religious	2	2	3.56	1
Medical	2	2	2.70	1
Shopping/service	21	7	1.97	2
Gym/exercise/sports	3	2	2.98	1
Visit friends/relatives	3	2	4.49	2
Meal related	6	3	2.28	1
Relax/entertainment	3	2	5.02	2
Other	12	2	3.50	1

BEVs with ranges from 45 miles to 100 miles are shown in Fig. 9, for scenarios with Level 1 (1.44 kW) and Level 2 (3.3 kW) infrastructure located at all dwelling locations. Both the BEV feasibility, defined above, and the VMT feasibility, defined by the vehicle miles traveled ratio, are illustrated. Fig. 9 results demonstrate the maximum feasibility with only the limits imposed by vehicle range and charging power; by assuming EVSE is located at all dwelling locations, the results remove the issue of charger availability. As a baseline, the BEV feasibility with charging locations limited only to home is shown.

For Level 1 charging, feasibility increases with vehicle range from 45 miles to 80 miles, but becomes saturated beyond 80 mile vehicle range. Level 2 charging exhibits continuously increasing feasibility with longer range BEVs. These results demonstrate the importance of higher power charging for BEVs, in particular for BEVs with longer range capability. Either larger capacity batteries or higher power charging is necessary to increase feasibility. Additionally, Fig. 9 shows that home charging alone can meet the needs of most drivers.

Fig. 10 provides results of charging cost and infrastructure requirements, defined to be the ratio of charging events to the total dwelling events. For instance, all scenarios point out that all vehicles would charge at home, so the charging events at home equal the total dwelling events at home. Contrarily, even if Level 1 EVSE were located at all workplaces, a scenario with 60 mile BEVs would only utilize 48% of those chargers. The optimization leads to a 100% home charging requirement, which is an intuitive conclusion since home is the location where vehicles have the longest dwelling time and the period coincides with low charging cost and low electricity demand. As for work place and public charging locations, Level 2 charging shows a significant potential for reducing the infrastructure requirements. With Level 2 charging and a 60 mile range, work place charging decreases from 48% to 20% while public location charging drops from 17% to 6%. The charging cost tends to be fairly constant with different BEV ranges, but a 10% reduction can be achieved by upgrading from Level 1 to Level 2 infrastructure.

The two figures above demonstrate that Level 2 charging will play an important role to increase BEV feasibility and decrease infrastructure requirements at non-home locations, as well as to decrease the charging cost. However, the infrastructure upgrade costs required to install Level 2 charging differ substantially from Level 1 due to not only the EVSE unit costs, but also the secondary distribution system upgrades. These factors need to be evaluated thoroughly in future work.

An additional important aspect for future work is residential locations that do not have easily accessible Level 1 (or Level 2) charging such as most apartment buildings. California survey results show that 20% of residents live in apartments or condominiums that likely do not have access to readily available home charging.

#### 3.2.2. Charging profile

Fig. 11 shows the average 24 h optimal charging profile for a fleet of 60 mile range BEVs having access to Level 2 charging at all locations and using the PG&E PEV rate structure. Sixty mile range BEVs were chosen by adding a range safety factor to current commercial BEV performance [26]. Comparison to the results from the PHEV35 above (Fig. 8) shows that home charging still dominates the electricity consumption with a wider charging time from 12 am to 8 am due to the increased battery capacity. The energy consumption from home charging accounts for 93%, as shown in Fig. 12. A small portion of charging at the work place still appears in the early morning, before the peak pricing hour, but amounts to just 5% of the total energy. Other locations account for only 2% of the total energy. As the vehicle's all-electric range increases, the

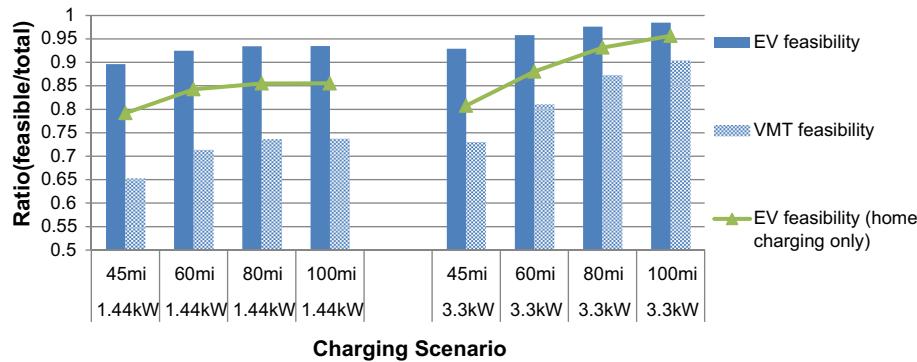


Fig. 9. BEV feasibility with different ranges and charging power options.

optimal charging profile shows that home charging plays an even greater role.

Fig. 12 shows the distribution of charging energy and charging events by location. As shown, a greater portion of charging events occur at non-home locations in comparison to the amount of energy delivered at non-home locations. The difference is due to charging characteristics as stated in As shown in Table 3, shopping and meal related activities represent the most used public charging locations; however, the average charged energy is only around 2 kW h, amounting to only about 5 miles of additional range per vehicle per day. As mentioned in the previous section, more charging locations lead to more operating cost reductions, but infrastructure cost and EVSE capacity factors (not considered herein) should be taken into account when assessing the deployment of non-home EVSE. More economic analysis needs to be conducted to fully understand the feasibility of installing public charging infrastructure for PHEVs to accomplish a relatively small amount of operating cost reduction.

Table 3 shows a lower charging utilization factor at non-home locations. In contrast to PHEVs which have the ability to operate on gasoline power if the battery SOC is low, the EVSE requirement reflected by the charging events for BEVs must be met such that the historical travel pattern can be fulfilled. In this sense, the charging event chart for BEVs can be a blueprint to allocate EVSE.

### 3.2.3. Approximation of EVSE allocation

To promote PEV deployment, both policymakers and automakers are highly interested in the allocation of EVSE. However, research has not previously been conducted that addresses EVSE allocation quantitatively from the cost perspective. This study uses the charging activities distribution to approximate EVSE with a

focus on BEVs only, since non-home charging is determined to be not necessary for PHEVs.

As the details of Figs. 12 and 13 show, the charging event counts for both weekday and weekend have different patterns. The weekend has more charging activity at home, 87%, but work place charging shrinks to just 2% as the counts at other locations increase.

The two independent dwelling patterns of weekday and weekend require EVSE to fulfill BEV requirements for both cases. The proposed methodology is:

1. Take the total BEVs number in the interested area, e.g.  $N_{BEVs}$ .
2. Use the charging activity at home,  $P_{home}$ , as a baseline, since it is assumed that 100% of BEVs require home charging.
3. Approximate the amount of EVSE at other locations by the charging activity  $P_{location}$  for both weekday and weekend, as expressed below.

$$N_{EVSE, \text{Location, weekday}} = N_{BEVs} \times \frac{P_{location, \text{weekday}}}{P_{home, \text{weekday}}} \quad (13)$$

$$N_{EVSE, \text{Location, weekend}} = N_{BEVs} \times \frac{P_{location, \text{weekend}}}{P_{home, \text{weekend}}} \quad (14)$$

4. Take the maximum number of EVSE for each location.

$$N_{EVSE, \text{location}} = \max \{N_{EVSE, \text{Location, weekday}}, N_{EVSE, \text{Location, weekend}}\} \quad (15)$$

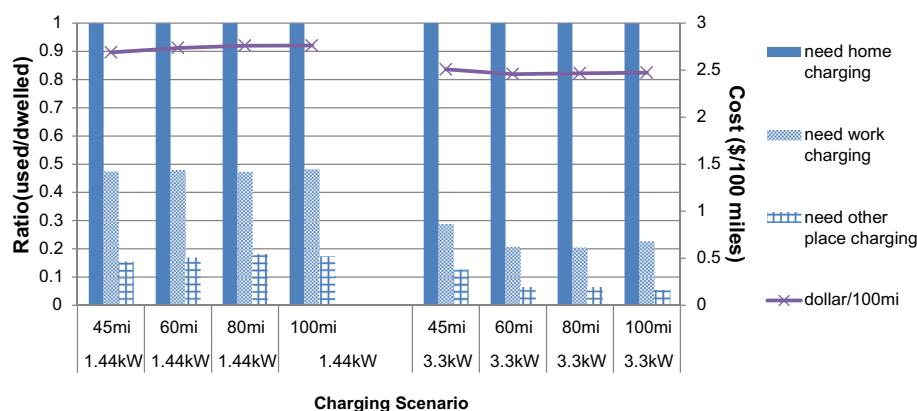


Fig. 10. Infrastructure requirements for different BEV ranges and charging power options.

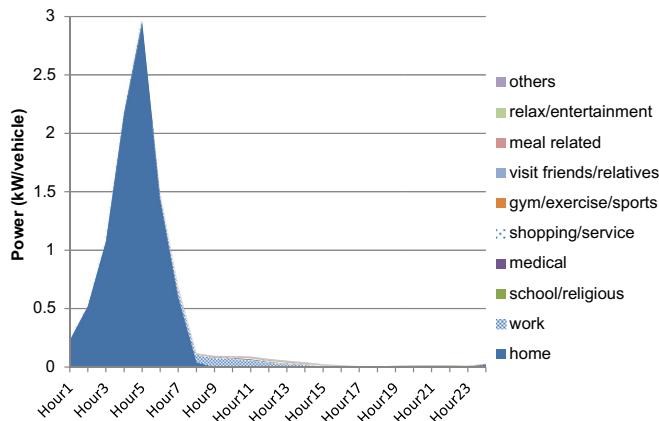


Fig. 11. BEV60 diurnal charging profile for optimal 3.3 kW charging.

The results are shown in Fig. 14. Approximately 80% of EVSE should be allocated to home locations and 9.6% should be placed at workplaces. The next locations that have most EVSE are shopping/services and visit friends/relatives.

### 3.2.4. Discussion

The EVSE allocation results do not include multiple vehicles using one EVSE during the same day, nor multi-unit dwellings where home charging may not be readily available. It can be predicted that with a large number of BEVs, some BEVs may share the same EVSE at the same location in the same day if their dwelling

schedules are not overlapped. In this sense, the result above is an upper bound for the quantity of non-home EVSE.

The EVSE allocation results are valid when the number of electric vehicles becomes considerable. In other words, when the deployment of BEVs is small, more non-home EVSE is required than the results show. For instance, if there is only one BEV on the road, the infrastructure has to cover all of that vehicle's travel patterns, so multiple EVSE are required at different locations. With increased BEVs, a specific public charging location can be used by different users in different days and times. The ratio of number of non-home EVSE per vehicle drops as more BEVs are deployed.

While the results provide key insights into EVSE allocation, it is difficult to use the results as a detailed rollout plan. First, the NHTS does not show the geographic coordinates for the trip destinations, so the model cannot allocate EVSE spatially. Therefore, more geographically specific travel pattern data will be beneficial. Secondly, the small percentage of EVSE at public locations or workplaces and the large amount of potential candidate charging locations lead to a discrepancy. For example, suppose there are 200,000 BEVs in southern California, then the quantity of EVSE required for work place sites is 23,983 according to the model. There are over 300,000 workplaces in Los Angeles and Orange County [32] indicating that actual distribution of the EVSE would depend on a variety of factors such as parking lot capacity, average dwelling time, and proximity to BEV ownership. The analysis herein provides a statistical approach to allocating infrastructure between location types, but does not determine the exact locations for the charging infrastructure.

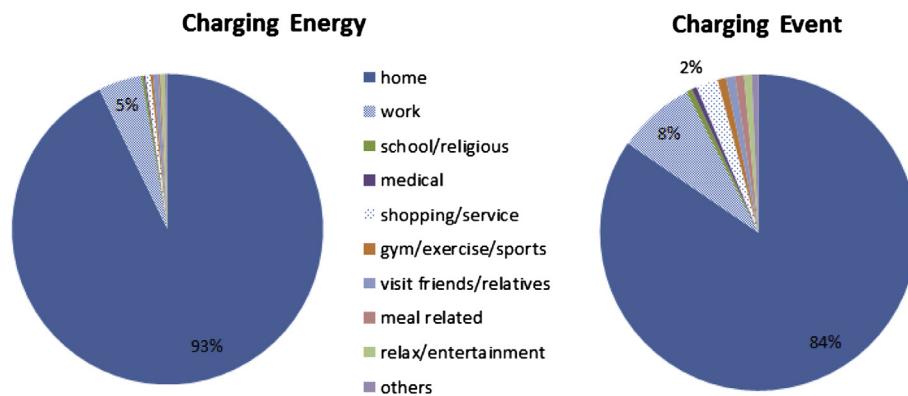


Fig. 12. BEV60 charging energy and event distribution for optimal 3.3 kW charging.

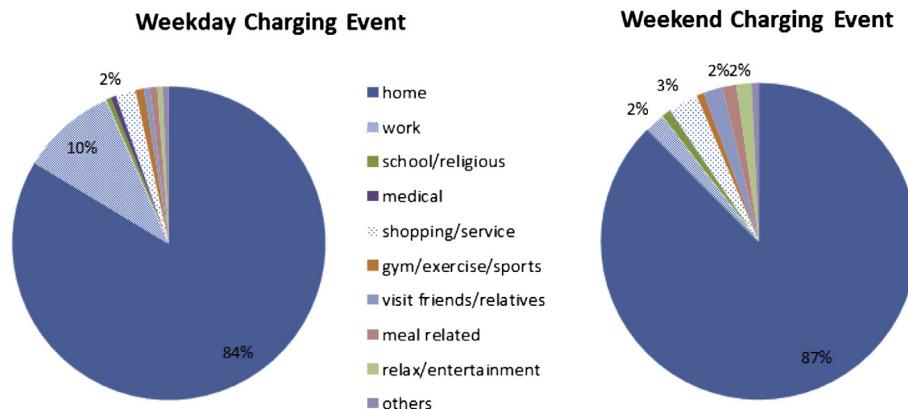


Fig. 13. Comparison of the charging event distribution for weekday and weekend.

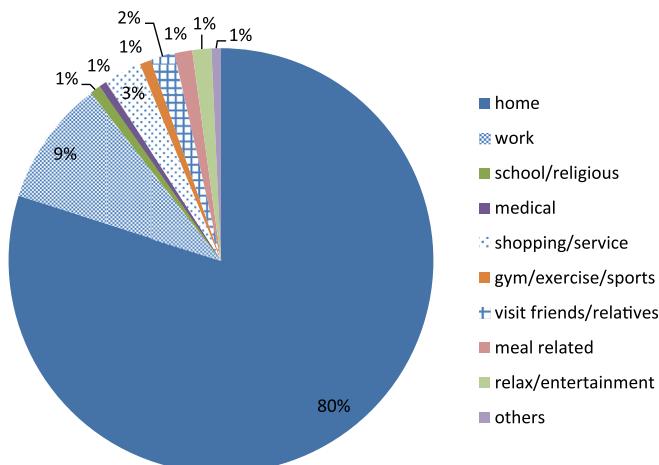


Fig. 14. EVSE allocation approximation.

DC fast charging should also be considered in the future within the context of a whole charging infrastructure system. DC fast charging can increase BEV feasibility when Level 2 charging cannot satisfy the demand; for example, during trips greater than 60 miles for a BEV60. The number and allocation of fast charging stations have the potential to be exactly optimized [33].

#### 4. Conclusions

A model with smart charging, smart charging with fuel price, optimal charging and operating for PHEVs, and optimal charging for BEVs, has been developed and applied. Most charging infrastructure options have been included in the model. From the results, analysis, and discussion above, the following conclusions can be drawn:

1. The model results and real EV project charging data show high correlation for a case with flat electricity rates and for a case with time-of-use rates, such that the model is verified to capture the real charging behavior as well as the hypothesis that people's charging behavior tends to minimize their costs. The study adopts California as an example by using the NHTS, but the methodology can be used for other geographic areas and vehicle travel pattern data.
2. The model results demonstrate a different infrastructure strategy for PHEVs and BEVs.

For PHEVs:

- All charging infrastructure options show substantial operating cost reduction for PHEVs compared to traditional hybrid vehicles, while the magnitude has significant variation, from 3.5 to 7.5 dollars/100 miles.
- The advanced charging time strategy results in the largest reduction in operating cost.
- The benefit of high charging power can be effective with the right time strategy.
- Although the use of more non-home charging locations can further reduce the fuel reduction and operating cost for PHEVs, the activity distribution from smart charging with fuel price and optimal charging indicate that more than 30% of charging will take place at non-home locations to garner a meager 1 dollar/100mile operating cost reduction. Consequently, society should carefully consider the overall benefit of non-home EVSE investment for PHEVs.

For BEVs:

- Unlike PHEVs, sufficient EVSE must be installed to satisfy BEVs.
- Level 2 charging plays an important role in increasing BEV feasibility defined in this paper, as well as decreasing EVSE at non-home locations dramatically, and cutting the charging cost by 10%.
- BEV60 shows a feasibility of 88% and 96% with 3.3 kW home charging only and non-restrictive charging, respectively.
- An optimal charging activity based EVSE allocation methodology was exercised to determine that 96% BEV feasibility requires 80%, 9% and 11% EVSE allocated for home, work and other places, respectively. This result can be used as a guide for EVSE investment. More work needs to be done in terms of the detailed rollout plan, such as using geographic enabled travel pattern data, considering parking capacity for a specific dwelling location, and integrating Level 3 DC fast charging into the model.

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